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Art. XX.—*The Sensitiveness of Photographic Plates to X-rays.*

BY

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(With Four Figures in the Text).

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This work was undertaken in order to determine the relation existing between the exposure and the resulting optical density of a plate exposed to X-radiation, and the type of plate most suitable for radiographic work. On the first question (the relation between exposure and density) work had previously been done by Salomonson[1] and by Hodgson.[2]

The plates under investigation were given a known exposure, developed in a standard manner and their densities were measured by a polarisation photometer.

For generating the X-rays a Coolidge tube excited by an induction coil was used, the potential across the tube being regulated by adjusting the length of the alternative spark-gap of the coil until a spark passed occasionally.

It was assumed that the exposure was proportional jointly to the energy of the X-radiation and to the time of exposure. The corresponding law for light is the Bunsen-Roscoe reciprocity law that, for equal densities of the photographic plate, the product I.t of intensity of light and time of exposure is constant. This law is not correct, and has been replaced by the Schwarzschild law that $I.t^p$ is constant for equal densities. The value of the constant p depends on (1) the kind of plate used, (2) the development,[3] (3) the density of the plate, and (4) the colour of the light used.[4] Stark[5] proposed the formula that $k.I.^m t^n$ is constant for equal densities, where k, m, n are constant for small variations of I. and t. Kron[6]

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1 Salomonson. Proc. Amsterdam Acad. xviii . 1916, p. 671.
2 Hodgson. Amer. Journ. Roent, 1917, p. 610.
3 Koch. Ann. d. Phys , iv., 30, 1909, p. 841.
4 Parkhurst. Astrophysikal. Jour., 30, 1909.
5 Stark. Ann. d. Phys., iv., 35, 1911, p. 461.
6 Kron. Publikationen des Astrophysikalischen Observatoriums zu Potsdam, No. 67, 1913.

tested the Schwarzschild law over a wide range of intensities, and found it to hold only for extreme values of the intensity. For a certain range of intensity he found the Bunsen-Roscoe law to be true.

Experiments were made in order to test the truth of the assumption that, when the product of energy of X-radiation and of time of exposure was constant, the photographic effect is the same. The energy of the X-radiation is, with the other conditions constant, proportional to the current flowing through the tube. The two halves of a plate were exposed separately; the current for the second exposure was 1/100 of the current for the first exposure, the time of exposure being correspondingly increased to 100 times its original value. After development it was found that the densities of the two halves of the plate were widely different, showing that the product of energy of radiation and of time of exposure does not determine the density.

In the small range of currents used in this work, however, (from .03 to .06 milliampere) the statement that density is jointly proportional to the energy of radiation and to the time is approximately true. This conclusion is verified by measurements made by Kröncke.[1] His results are shown below :—

Current	1.0	2.0	3.0	4.0	milliamperes.
Time	12.0	6.0	4.0	3.0	minutes.
Density	1.09	1.15	1.16	1.15	

The energy of the cathode-rays is jointly proportional to the current flowing through the tube and to the electrical pressure applied to the tube. The fraction of this cathode-ray energy converted into X-ray energy in the Coolidge tube is proportional to the square of the velocity of the cathode-rays, i.e., to the first power of the pressure.[2] Hence we define exposure in radiography as

$$e^2ct/d^2 \text{volt}^2.\text{ampere.sec.cm}^{-2}.$$

where, e volts = pressure applied to tube.
c amperes = current through tube.
t seconds = time of exposure.
d cms = distance from source (anticathode) to plate.

The average current was measured by an unshunted milliammeter connected in series with the tube and induction coil. The cathode of the tube (to which the milliammeter was connected) was earthed. The time of exposure was measured by a stop-watch.

1 Kröncke. Ann. d. Phys., iv., 43, 1914, p. 687.
2 Rutherford and Barnes. Phil. Mag., xxx., 1915, p. 361.

Each plate was exposed in from five to eight strips, the exposures of successive strips increasing in a constant ratio. There was also a fog-strip which was shielded from radiation the whole time.

The distance from plate to anticathode was 100 cms. The currents used varied from .03 to .06 milliampere. The pressures used were 31.5, 73.0, 83.0 kilovolts corresponding to spark-gaps of 1.5, 5.0, 7.0 cms., respectively between spheres of 6.5 cms. diameter, the cathode being earthed.[1] The minimum wave-lengths of the radiation were, therefore, $.390 \times 10^{-8}$, $.173 \times 10^{-8}$, and $.152 \times 10^{-8}$ cms. respectively.[2] The wave-lengths of the K and L characteristic radiation for silver are $.56 \times 10^{-8}$ and 4.17×10^{-8} cms., and for bromine 1.05×10^{-8} and 8.48×10^{-8} cms.

The developer was one often used in radiography, as follows[3]:—

Solution A.

Hydroquinone	25 gms.
Potassium metabisulphite	25 gms.
Potassium bromide	25 gms.
Water	1000 c.c.

Solution B.

Potassium hydroxide	50 gms.
Water	1000 c.c.

The two solutions were mixed in equal proportions immediately before use, and the plates were developed at a temperature of 20° C. for 4 minutes. After 4 minutes' development the density due to the exposure had reached its maximum value and further development only increased the fog-density of the whole plate. In order to verify this an Ilford X-ray plate was cut into three pieces, which were exposed simultaneously. On each piece there was a strip which received an exposure of 8.7×10^3, one which received 4.1×10^4 volt.^{2} amp. sec. cm^{-2}, and an unexposed or fog strip. The three plates were then developed at 20° C. for periods of 3, 4, and 5 minutes respectively. The resulting densities are tabulated below under D_1 and D_2, which are the densities due to the exposures given, the fog-density, D_f, having been subtracted from the measured density.

1 F. W. Peek. "Dielectric Phenomena in High Voltage Engineering," p. 89.
2 Hull. Phys. Rev., vii., 1916, p. 156.
3 Sahni. Phil. Mag., xxix., 1915, p. 836.

Time of Development.		D_1		D_2		D_f
3 minutes	-	1.83	-	2.49	-	.37
4 minutes	-	2.52	-	3.42	-	.45
5 minutes	-	2.57	-	3.56	-	.58

Evidently, after 4 minutes' development, the density due to any exposure does not appreciably increase, though prolonged development does increase the fog-density.

The transparency of a plate is defined as the ratio of the intensity of the transmitted light to that of the incident light, i.e. $T = \frac{I_t}{I_i}$ The opacity, O, is the reciprocal of the transparency, and the density, D, is defined thus :—

$$D = \log_e O = \log_e \frac{I_i}{I_t}$$

A polarisation method was employed in measuring the density. Light from the source S was reflected from the plane mirror M, and was viewed through O, where it illuminated half of the field of view. The other half of the field was illuminated by light from S^1, which had been transmitted through a pair of Nicol prisms. Metallic filament lamps in parallel were used as the sources of light.

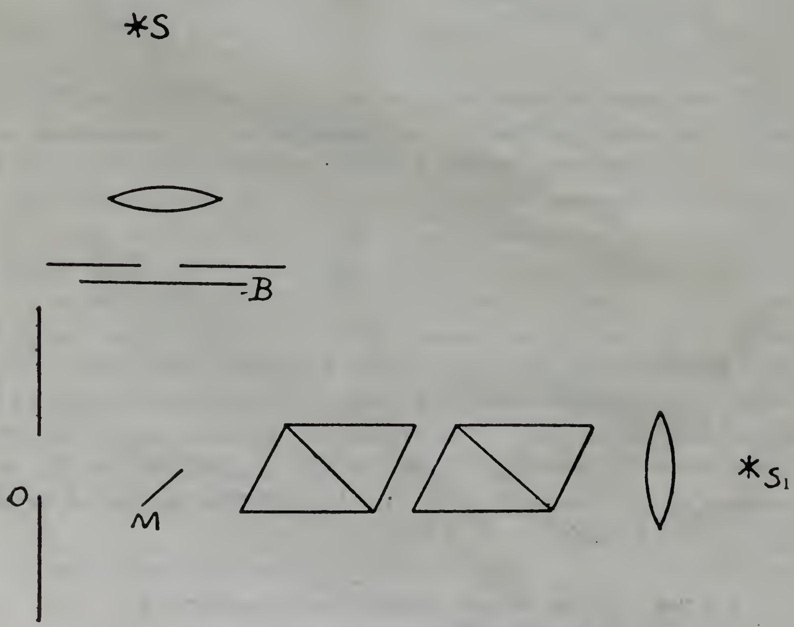


Fig. 1.—Polarization Photometer.

A plate of green glass was placed in the path of each beam of light so as to eliminate any difficulty due to difference of colour in the two halves of the field of view. The analysing Nicol was rotated until the two halves of the field of view matched; the angle θ between the two Nicols was read, and the intensity of the light from S was therefore proportional to $\cos^2\theta$. The photographic plate B was now placed in position, and the analysing Nicol was rotated until the field again appeared uniform. If the angle between the two Nicols was now θ', the intensity of the light transmitted through the plate was proportional to $\cos^2\theta'$. Hence the density of the plate was obtained as $\log_e \frac{I_i}{I_t}$, or $\log_e \frac{\cos^2\theta}{\cos^2\theta'}$. The density of the fog strip was also measured and was subtracted from the measured density of each of the other strips to give the true density due to the exposure.

When, for any given plate, the density was plotted against the logarithm of the exposure, the curve obtained was similar in character to that for light. In the region of under exposure the curve was convex to the axis of log E (see Fig. 2), but for densities greater than about 1.0 a straight line was obtained, so that in this neighbourhood the density of a plate is given by $D = \gamma . \log_e \frac{E}{i}$. The quantity i is the inertia of the plate, and is the exposure corresponding to the density of 0 if the straight line law held for all

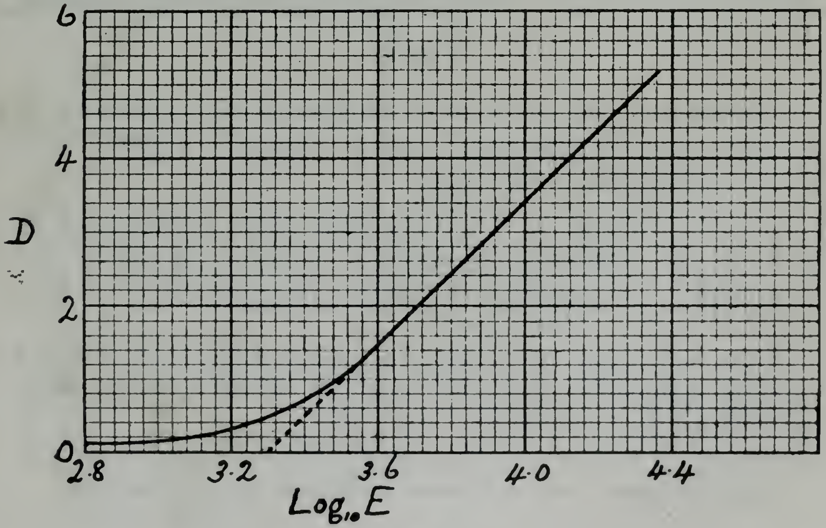


Fig. 2

values of the exposure. For the exposures we have used we find that the inertia of a plate is independent of the time of development. In the table below, D_1 and D_2 are the densities resulting from exposures of 8.71×10^3 and 4.10×10^4 volt^2.ampere.sec.cm^{-2} on Ilford X-ray plates.

Time of Development.	D_1	D_2	D_2/D_1
3 minutes	1.83	2.49	1.36
4 minutes	2.52	3.42	1.39
5 minutes	2.57	3.56	1.36

Since the ratio D_2/D_1 is independent of the time development, it follows that the exposure corresponding to a density of o, i.e., the inertia, is independent of the time of development. Hurter

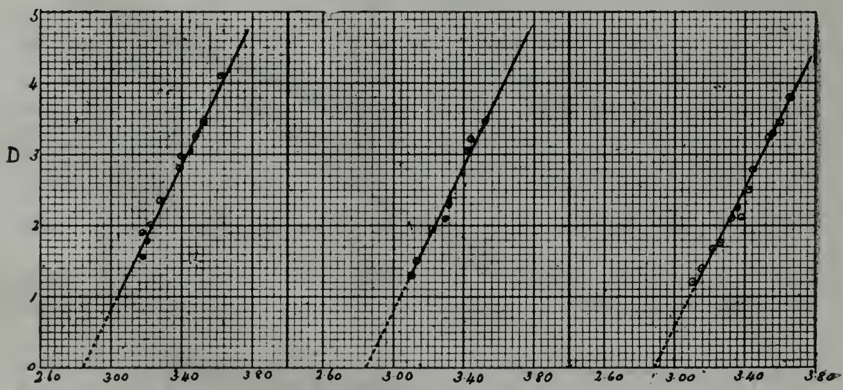


Fig. 3

and Driffield[1] have proved it to be independent also of the kind of developer used. The so-called speed of a plate is a quantity inversely proportional to the inertia.

γ, or the increase in D corresponding to an increase of 1 in $\log_e E$, is the contrast of the plate. Its value depends on the development, and reaches a maximum when the plate has been developed to its maximum density.

In the table below are tabulated (1) the inertia of the plate (in volt^2.ampere.sec.cm^{-2}), (2) the contrast, and (3) the minimum value obtained for the fog density.

1 Hurter and Driffield. Jour. Soc. Chem. Ind., 9, 1890, p. 455.

	Plate.	Inertia.	Contrast.	Fog-density.
1	Paragon X-ray	1.17×10^3	2.4	.59
2	Paragon X-ray	.74	2.3	.23
3	Diagnostic X-ray	.71	2.2	.30
4	Sunic X-ray	1.00	2.3	.60
5	Seed X-ray	1.12	1.9	.45
6	Wratten X-ray	1.95	2.2	.51
7	Wellington X-ray	1.70	2.0	.24
8	Austral X-ray	4.68	3.1	.40
9	Imperial X-ray	1.26	1.6	1.44
10	Cramer X-ray	2.14	1.9	.55
11	Ilford X-ray	2.19	1.9	.36
12	Imperial Special Rapid	1.44	1.5	.18
13	Imperial Special Sensitive	.81	1.3	.38
14	Austral Standard (Sun)	1.58	1.4	.27
15	Austral Standard (Extra Rapid)	3.71	1.2	.35
16	Austral Standard (Extra Rapid) II.	1.23	1.2	.59

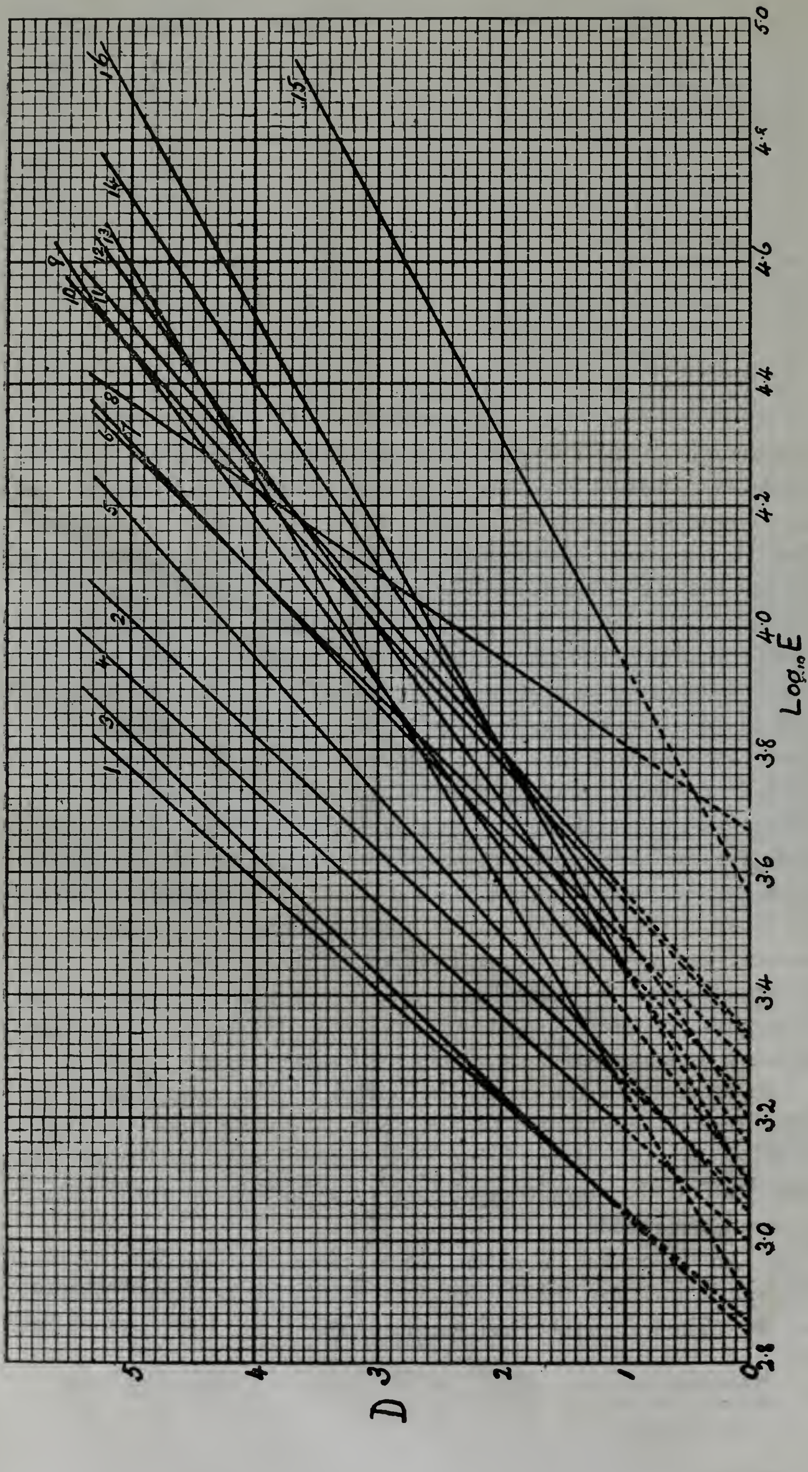
Although all the Paragon X-ray plates used were from the same batch, two distinct exposure lines were obtained, both giving the same contrast, though the inertia was much greater in one case than in the other. Apparently, some of the plates had received a thicker coating of emulsion than others.

Salomonson[1] found that, while the inertia of any given type of plate was always the same, whatever the hardness of the rays, the slope of the exposure line and, therefore, the contrast of the plate, was greater for the more penetrating radiation. Hodgson,[2] on the other hand, found in his measurements of the density of Seed X-ray plates, that the contrast diminished with the increasing hardness of the radiation. In this work, however, the exposure lines for the three different pressures, that is for three different wave lengths, were found to be coincident. The inequalities in the thickness of the emulsion on the plates are more than sufficient to account for any departures from the straight line. The actual points obtained with the Diagnostic X-ray plate for each of the three pressures used are shown in the graph Fig. 3; the three exposure lines are coincident within the limits of accuracy possible.

The accuracy of the results is limited by the variations in the thickness of the emulsion on the plate. In some cases variations even in the small strips being photometered were noticeable. In order to find the magnitude of errors due to this cause the following tests were made:—

(1) An unexposed Wratten X-ray plate (half-plate size) was developed and the fog-density was measured at eight different points. The values obtained were:—1.62, 1.56, 1.62, 1.83, 1.82,

1 Salomonson. Loc. cit.
2 Hodgson. Loc. cit.


D
0
1
2
3
4
5
$Log_{10} E$
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
1
2
3
4
5
6
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15
16

Fig. 4

1.63, 1.85, 1.71; the average departure from the mean value of 1.71 was .10.

(2) A Paragon X-ray plate (size 10 in. x 8 in.) was given an exposure of 2760 volt^2-ampere-seconds per cm.^{2} After development its density was measured at twenty points, the values obtained being:—3.58, 3.94, 4.08, 4.21, 4.73, 4.73, 4.59, 4.33, 4.14, 3.74, 4.08, 4.21, 4.14, 3.50, 4.04, 4.21, 4.59, 3.50, 3.91, 4.08; the average departure from the mean value of 4.12 was .26.

Direct measurements of the mass of silver salts per square centimetre of each plate verified the existence of these inequalities.

Mr. Jones, of the Kodak (Australasia) Ltd. kindly prepared plates of the same type as the Austral Standard (Extra Rapid) plates, but having a double coating of emulsion. This plate is tabulated as Austral Standard (Extra Rapid) II. As can be seen from the exposure lines, this led to an increase in speed, though the contrast remained practically unaltered. Unfortunately, however, the fog-density was also increased, and, as the plate was always somewhat stained by the developer, it was difficult to measure its density.

In obtaining the mass of silver salts on the plate, the emulsion, after having been dissolved off in boiling water, was digested in nitric acid and filtered through a Gooch crucible. Two measurements were made for each plate and the differences between the values obtained confirmed the existence of inequalities in the thickness of the emulsion. The total mass of emulsion and gelatine together was also measured, and the percentage of silver salts in the emulsion was calculated.

The table below gives the two values obtained for the mass of silver salts per unit area of the plate, and also the average value of the percentage by mass of silver salts in the emulsion. From these figures it appears that the speed of a plate does not depend entirely on the mass of silver present in the emulsion:—

Plate.	Mass of Silver Salts per cm^2. 1	Mass of Silver Salts per cm^2. 2	Mass of Silver Salts per 100 mgms. of Emulsion.
	mgms.	mgms.	mgms.
Paragon X-ray	2.4	2.6	48
Wellington X-ray	2.2	2.4	39
Wratten X-ray	2.5	2.6	38
Ilford X-ray	2.4	2.6	45
Imperial X-ray	3.2	2.9	38
Austral Standard (Sun)	1.3	1.5	—
Austral Standard (Extra Rapid)	1.0	.8	29
Austral Standard (Extra Rapid) II.	2.5	2.9	45

SUMMARY.

1. Exposure in radiography is defined as energy of incident X-rays per square cm.

2. It is found that within a limited range of exposure the density of the developed "image" produced in a silver emulsion is proportioned to the logarithm of the exposure.

3. The density of the image produced by a given quantity of incident energy is independent of the wave length of the radiations used in these experiments.

4. The inertia, contrast, and fog density of a number of plates for low radiation intensities is stated.

5. The speed (that is, the exposure required to produce a given density) of a plate depends on the nature of the emulsion, and the mass of silver per unit plate area.

6. Contrast depends on the nature of the emulsion and is apparently independent of the mass of silver per unit area.

The experiments are being continued.